

Energy dependence of the v_2 -scaling and the QCD phase boundary

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Abstract. In high-energy nuclear collisions at RHIC ($\sqrt{s_{NN}} = 60 \sim 200$ GeV), the quark coalescence has been identified as the process for hadronization. As a result, one observes a scaling in elliptic flow parameter v_2 and hadron type dependence (within $2 < p_T < 5$ GeV/c region) in nuclear modification parameter R_{AA} . On the other hand, in a given collision when the center of mass energy is not sufficiently high to create partonic matter, one would not expect the scaling in the final observed v_2 . Hence, the scaling provides us a sensitive tool in order to search for the possible phase boundary in the hot/dense matter dominated by either partonic or hadronic degrees of freedom. In this paper, we will report the results from analyzing the energy dependence of v_2 for identified hadrons from Au+Au collisions for energy ranging from 200 GeV to 5 GeV. Data from transport models are used in our analysis. Without the partonic coalescence, the scaling is absent.

1. Introduction

Since the very moment of the discovery of Quantum chromodynamics (QCD), scientists have speculated that under extreme conditions, high temperature and/or high density, a hadronic system will be transferred into a de-confined state where quark and gluon degrees of freedom become dominate. Calculations based on modern quantum gauge theory have demonstrated the transition between a hadronic to a partonic system. More recently, theoretical calculations have also indicated a complicated rich structure of the QCD matter that varies as a function of baryon density and temperature.

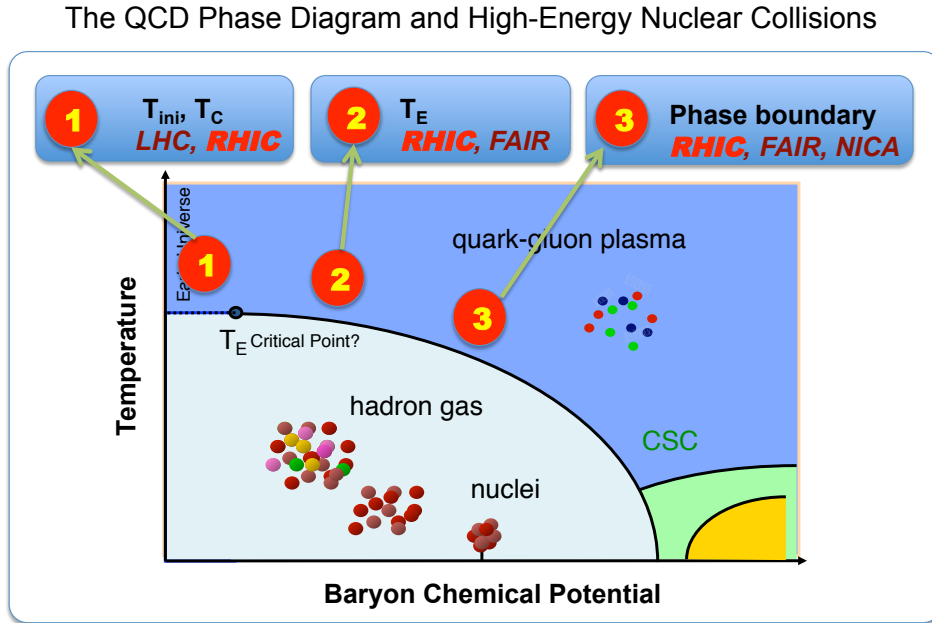


Figure 1. (Color online) Schematic QCD phase diagram for nuclear matter. The solid black line shows the phase boundary between hadronic gas and quark-gluon plasma. At high energy or low baryon chemical potential, the phase boundary ends and the phase transition turns to a cross-over. At very high baryon density, new phases such as color superconductor (CSC) or Quarkyonic emerge. Current and future facilities for study the QCD phase diagram are indicated at the top of the figure.

Experimental results from collisions at top energy ($\sqrt{s_{NN}} = 200$ GeV) at RHIC have provided evidence for the creation of strongly interaction matter at an energy of the order of 30 times that of the normal nuclear matter [1, 2]. Under such condition, as predicted by the Lattice Gauge Theory calculations, the transition from hadronic matter to quark-gluon plasma is a smooth cross-over. One of the most crucial observations is the enormous partonic collectivity in Au+Au collisions and hadrons are formed via the novel coalescence process in contrast to the conventional fragmentations, manifested in the so-called Number of Constituent Quark (NCQ) scaling in v_2 . At give collision centrality, the scaled anisotropy parameter v_2/n_q for all hadrons becomes identical. Here

n_q is the number of quark within the hadron under study. The observed scaling in v_2 is a consequence of the de-confined matter produced in collisions at RHIC [3, 4, 5, 6].

Now there are two important questions regarding the QCD phase diagram. The first one is about the nature of thermalization in high-energy nuclear collisions at RHIC and future LHC. This includes how the thermalization is achieved and how long it lasts. It involves crucial question of the parton distribution function from the in-coming nuclei and the dynamics of the interactions amongst the quarks and gluons. This question will be addressed experimentally by the RHIC heavy quark upgrades in the near future. Hadrons contain charm and bottom quarks will be constructed directed via the hadronic decays that provide the information on the collectivity of heavy quarks in such collisions.

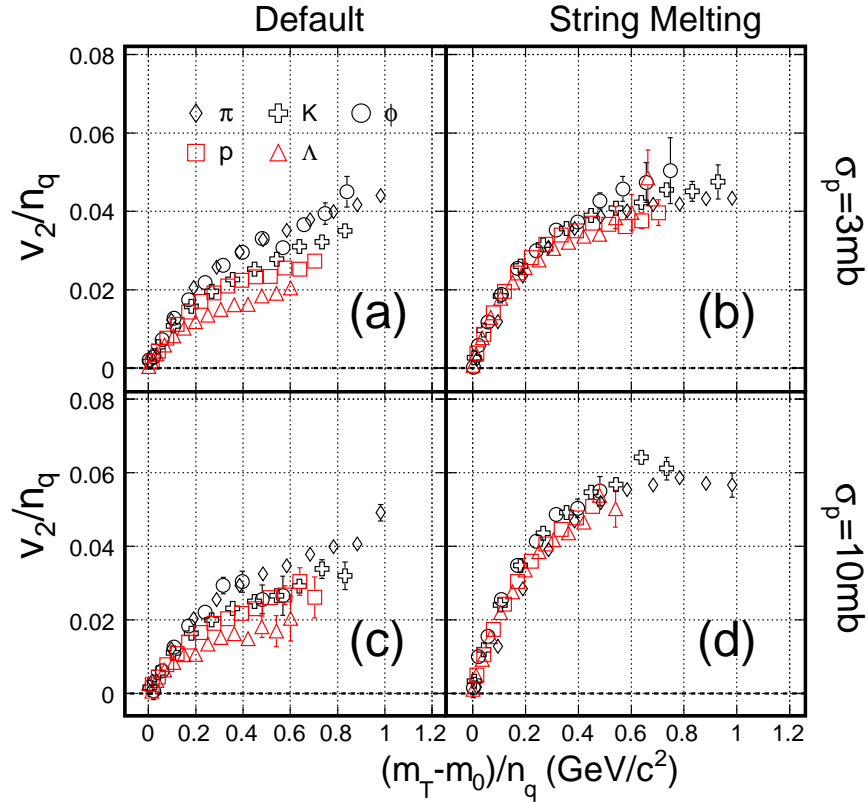


Figure 2. (Color online) AMPT model results of number of constituent quark scaled v_2/n_q versus scaled transverse mass $(m_T - m_0)/n_q$, for π , p , K , ϕ and Λ , from $\sqrt{s_{NN}} = 9.2$ GeV Au+Au minimum bias collisions. Plots (a) and (c) show the results from default and plots (b) and (d) are from string-melting case. Two different partonic cross sections were used in the tests.

The second important question: How does the QCD phase diagram look like? A phase diagram tells us how matter organize itself under give conditions, it is a map of the structure for the matter. In this case, the degrees of freedom is quarks and gluons. Such map connects the known world for us to the beginning of the university at high temperature and the core of neutron stars at the extreme baryon density. Till now, the map does not exist. Theoretically there has been lots of progress in the past few

years in predicting the phase diagram [ref...] although large uncertainties remain in the calculation. At the vanishing baryon chemical potential, the Lattice calculations predicted a cross-over at a crossing temperature $T_c \sim 170 - 190$ MeV [7]. A recent predictions on the end point of the first order phase transition, T_E , indicated as the solid-black-line in Fig. 1, can be found in Refs. [8, 9]. Experimentally, vary the beam energy will allow us to map the QCD landscape assuming the system reached the state of thermalization. For RHIC, the energy span is from $\sqrt{s_{NN}} = 200$ GeV to 5 GeV. the corresponding rang of μ_B is 20 - 540 MeV. At both FAIR and NICA, the reach of baryon density could be extended to 650 MeV. At LHC energy, the μ_B is about 5 MeV, sufficiently close to ‘zero’ baryon density.

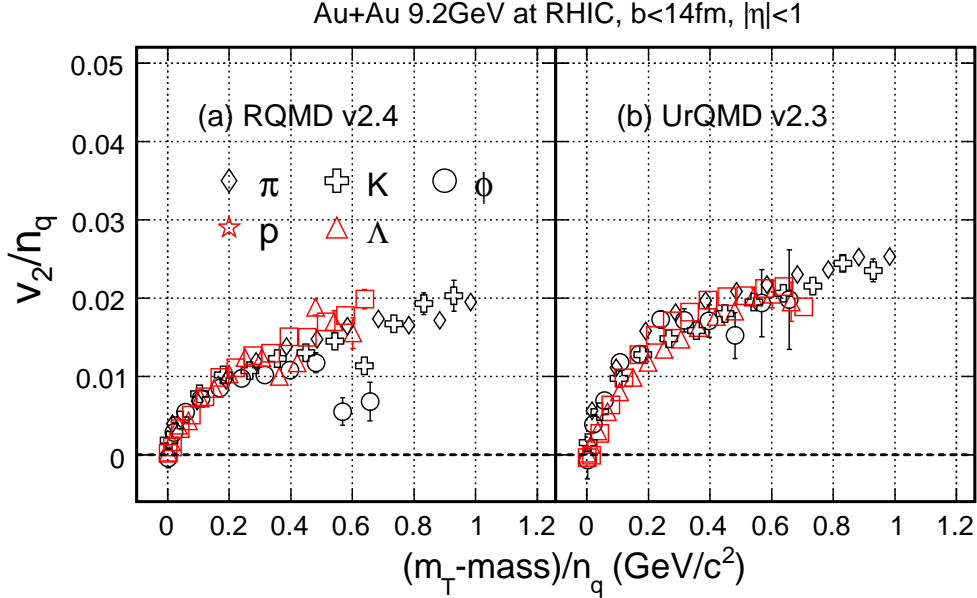


Figure 3. (Color online) The same as in Fig.2 but from hadronic transport models RQMD v2.4 (a) and UrQMD v2.3 (b).

In this paper, we propose an observable what will be sensitive to the possible boundary between hadronic and the de-confined partonic phases. As mentioned above, in $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions, the v_2 NCQ scaling for all observed hadrons including both multi-strange hadron ϕ -meson and Ω -baryon. The scaling can be explained by the coalescence, $q + q \rightarrow h + x$, for hadron production in such collisions therefore provided a strong evidence for the formation of sQGP at RHIC. The AMPT model with string-melting [10, 11] and parton coalescence, indeed, reproduced the observed scaling for collisions at 200 GeV with a 10 mb partonic cross section. Since the NCQ- v_2 scaling is an unique finger print of the de-confined mater, at sufficient low collision energy where hadronic degrees of freedom dominates the evolution, one does not expect such scaling in v_2 . In order to establish the observable, we performed several simulations with AMPT [10, 11], RQMD and UrQMD. While AMPT default mode, RQMD and UrQMD deal only hadronic interactions where hadrons are formed

via string fragmentations, AMPT string-melting mode allows for testing the coalescence process.

In Fig. 2, we show AMPT model results of number of constituent quark scaled v_2/n_q versus scaled transverse mass $(m_T - m_0)/n_q$, for π , p, K, ϕ and Λ , from $\sqrt{s_{\text{NN}}} = 9.2$ GeV Au+Au minimum bias collisions. About 25M events were used in the study. Plots (a) and (c) show the results from default and plots (b) and (d) are from string-melting case. Two different partonic cross sections were used in the tests. As one can see in the figure, hadronic interactions *do not* lead to the scaling (left plots in Fig. 2) while the string-melting result to a clear and clean scaling (right plots in Fig. 2) for all hadrons studied here. Changing the parton interaction cross section does not bare any effect on the default mode but strongly affect the amplitude of the final value of v_2 in the string-melting mode. However, the feature of v_2 scaling is not affected. A similar conclusion was also tested at higher energy $\sqrt{s_{\text{NN}}} = 12.3$ GeV Au+Au collisions [12].

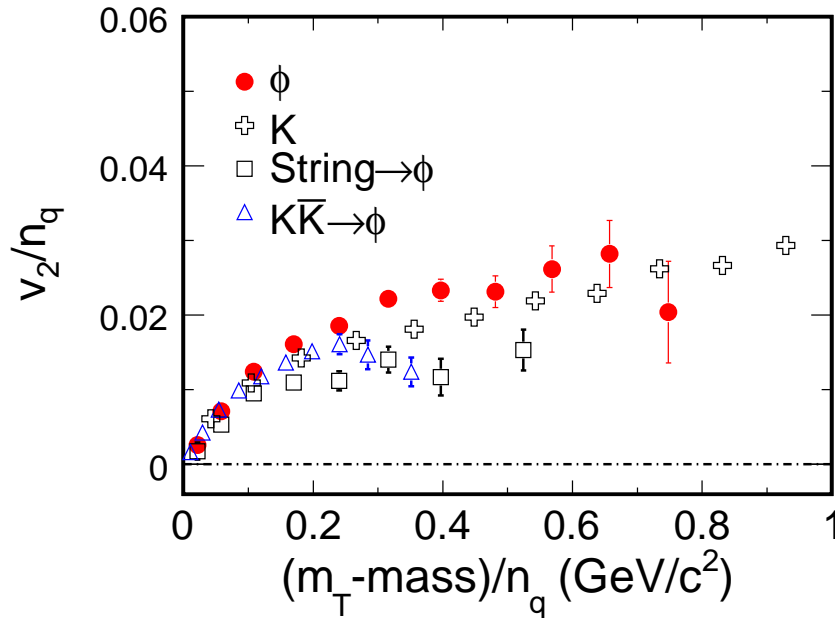


Figure 4. (Color online) The number of constituent quark scaled v_2/n_q versus scaled transverse mass $(m_T - m_0)/n_q$ for ϕ -meson. The UrQMD results are from the transport model UrQMD for $\sqrt{s_{\text{NN}}} = 9.2$ GeV Au+Au minimum bias collisions. For comparison, kaon results are also shown as crosses.

The results from hadronic transport model RQMD and UrQMD are shown in Fig. 3 left and right plot, respectively. It is interesting to observe that, since both model employ the value of hadronic interaction cross section from a additive quark model [13], the scaling is almost reproduced. Nevertheless, this apparent scaling *is* misleading as there two-third of the ϕ -mesons are from the fusion of kaons in both calculations. In case the NCQ scaling is valid in those model then v_2 of ϕ -meson should not scale.

In order to clarify this point, we have made more detailed study with the UrQMD model. The results of ϕ -meson v_2 from various sources are shown in Fig. 4. For

comparison, the kaon v_2 is also shown as crosses in the figure. The result shows the scaled ϕ v_2 is higher than kaon's. This is caused by the KK fusion process in the model calculation. As expected, the directly produced ϕ -mesons (open-squares) from string is much lower than that of kaons, this is partly due to the fact that string decayed ϕ mesons leave the system at a relatively early time and partly because ϕ itself does not interact in the hadronic medium. This is the primary reason we choose ϕ as a penetrating hadron probe [14, 15] for early partonic dynamics.

In summary, we propose to utilize the properties of the NCQ scaling of v_2 in the search for phase boundary in the future Beam Energy Scan program at RHIC. When scan from high to low beam energy, the broken of the scaling for identified hadrons, especially for the multi-strange hadron such as ϕ will signal a system where hadronic degrees of freedom dominant.

2. Acknowledgment:

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